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OBSERVING CONDITIONS FOR SUBMILLIMETER ASTRONOMY

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RESUMEN

Condiciones de observación consistentemente excelentes son cruciales para lograr los objetivos científicos de un telescopio. La astronomía submilimétrica es posible solamente en algunos sitios excepcionalmente secos, notablemente Mauna Kea, el plateau de Antártida, y la región de Chajnantor en los Andes al este de San Pedro de Atacama en el norte de Chile. Las mediciones de larga duración de la transparencia atmosférica a 225 GHz y 350 μm demuestran que las tres localidades cuentan con suficientes períodos de excelentes condiciones de observación. Las condiciones en el Llano de Chajnantor y en el Polo Sur son mejores con más frecuencia que en Mauna Kea. Las condiciones son mejores durante el invierno y por la noche. Cerca de la cima del Cerro Chajnantor, las condiciones son mejores que en el Llano de Chajnantor.

ABSTRACT

Consistently superb observing conditions are crucial for achieving the scientific objectives of a telescope. Submillimeter astronomy is possible only at a few exceptionally dry sites, notably Mauna Kea, the Antarctic plateau, and the Chajnantor region in the high Andes east of San Pedro de Atacama in northern Chile. Long term measurements of 225 GHz and 350 μm atmospheric transparency demonstrate all three locations enjoy significant periods of excellent observing conditions. Conditions on the Chajnantor plateau and at the South Pole are better more often than on Mauna Kea. Conditions are better during winter and at night. Near the summit of Cerro Chajnantor, conditions are better than on the Chajnantor plateau.

Key Words: atmospheric effects — site testing — submillimeter: general

1. INTRODUCTION

Star formation occurs deep within in dense interstellar molecular clouds permeated with obscuring dust. Heated by the optical and UV radiation emerging from nascent stars, the dust reradiates at longer, submillimeter wavelengths. Submillimeter observations provide, therefore, key information for understanding the details of star formation and for tracing its progress throughout the history of the universe. In addition to the continuum, there is a rich line spectrum of molecular rotational transitions and atomic fine structure lines in the submillimeter, which provide essential data for understanding the cycle of material from the interstellar medium through stars and back again.

Earth's atmosphere poses an serious impediment to submillimeter observations, however, because water vapor and other molecules absorb strongly at these wavelengths. Atmospheric transmission declines dramatically at high frequencies, especially under wetter conditions (Figure 1). Observations are possible only through discrete windows delineated by pressure broadened transitions.

Although spacecraft such as *Herschel* are not limited by the atmosphere and can provide superlative science return, mission costs are high and the practical telescope size is limited. Telescopes on the ground, on the other hand, can be much bigger, are less expensive, and enjoy easier access but require consistently superb observing conditions to achieve their scientific objectives. It is imperative, therefore, to thoroughly characterize a potential telescope site before embarking on construction.

2. SITES

Worldwide, the typical precipitable water vapor (PVW) is about 25 mm (Seidel 2002), high enough to preclude submillimeter observations. Because of the uneven distribution of tropospheric water vapor, however, a few exceptionally dry locations are suitable for observatories. Water vapor is concentrated in the lower troposphere with a typical scale height of 1–2 km, much less than the pressure scale height of 7–8 km. Deserts, by definition, are arid so accessible desert mountain summits are good candidates.

Three premiere sites for submillimeter astronomy are Mauna Kea, the Antarctic plateau, and the high Andes in northern Chile. Despite its location in the middle of the Pacific ocean, Mauna Kea enjoys good observing conditions because a temperature inver-

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sion frequently traps moisture well below the 4100 m summit altitude. Telescopes on Mauna Kea, including the CSO, the JCMT, and the SMA, pioneered submillimeter astronomy. Even though the air is close to saturated over the ice surface of the Antarctic plateau, the extreme cold, especially in winter, means the absolute humidity is very low. Several telescopes, including the SPT, now carry out mm and submm observations at the 2835 m high South Pole. The higher domes C (3230 m), F (3800 m), and A (4100 m) have been suggested for future observatories (Spinoglio & Epchtein 2010).

In northern Chile, the Atacama desert is arguably the driest in the world. The combined effects of a persistent high pressure cell over the eastern Pacific, a coastal inversion layer created by the cold Humbolt current, and a coastal mountain range prevent the prevailing westerly winds from transporting moisture into the region. To the east, the barrier of the high Andean cordillera hinders the flow of tropical convection from the Amazon. The consequent lack of glaciers, even on the highest peak in the region, Volcán Llullaillaco (6740 m), is unique for these altitudes and attests to the aridity (Messerli et al. 1993). On the 5000 m high Chajnantor plateau east of San Pedro de Atacama, several small telescopes have made important contributions and ALMA is nearing completion. The candidate site for CCAT is at 5612 m near the summit of Cerro Chajnantor overlooking the plateau (Radford et al. 2010).

3. TRANSPARENCY

Atmospheric transparency is *the* fundamental site characteristic because astronomical observations will be futile if cosmic radiation cannot penetrate the atmosphere. No countermeasures are available to improve the intrinsic transparency of the atmosphere over a site.

Atmospheric absorption imposes a twofold penalty. "The degradation in [system] noise temperature due to *absorptive elements* results from two effects: reduction in signal ... by ... absorption and introduction of noise by re-radiation..." (Penzias & Burrus 1973). This is true for both coherent (heterodyne) receivers and background limited bolometers. Because integration time is proportional to the square of the system noise, a small fractional improvement in transparency can yield a large improvement in observing efficiency.

4. ATMOSPHERIC SPECTRUM

At millimeter and submillimeter wavelengths, the atmospheric spectrum is dominated by strong resonant absorption lines of the major molecular species,

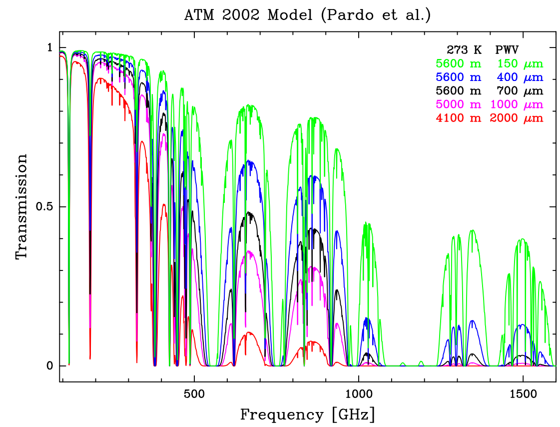

Fig. 1. Model atmospheric transmission spectra at submillimeter wavelengths for different amounts of precipitable water vapor (PWV) in temperate conditions (0°C) on high altitude (4000–5600 m) mountains. The relationship between PWV and transmission is not applicable under very cold, i.e., Antarctic conditions. Calculated with the ATM model (Pardo et al. 2001).

notably H_2O, O_2, and O_3 (Figure 1). Also pseudo-continuum absorption, which has both wet and dry components, arises from the far wings of strong infrared lines and is stronger at higher frequencies. Contemporary models, such as ATM (Pardo et al. 2001), *am* (Paine 2011), and Moliere (Urban et al. 2004), have been verified against spectroscopic measurements (Matsushita et al. 1999; Paine et al. 2000; Pardo et al. 2005). These models are parameterized by the barometric pressure, equivalent to the site altitude, and the vertical profiles of air temperature and water vapor. Because the shape of the vertical profiles usually can be assumed, values of the surface temperature and the total PVW are sufficient.

It is worth noting the principal submillimeter windows are delineated by rotational transitions between low energy states of water vapor (Figure 2). For a given atmospheric water vapor content, then, these states will be more populated, and the lines will be stronger, if the air temperature is very low. Detailed model calculations bear this out. At 225 K (Antarctic winter), the ratio of optical depth to PVW is about twice as high as at 275 K (temperate locations).

5. TIPPING RADIOMETERS

Microwave sounding of the atmosphere was pioneered by Dicke et al. (1946), who inferred the atmospheric absorption from measurements of brightness at different zenith angles. This tipping radiometer technique remains standard for monitoring atmospheric transparency. Continuum radiometers mea-

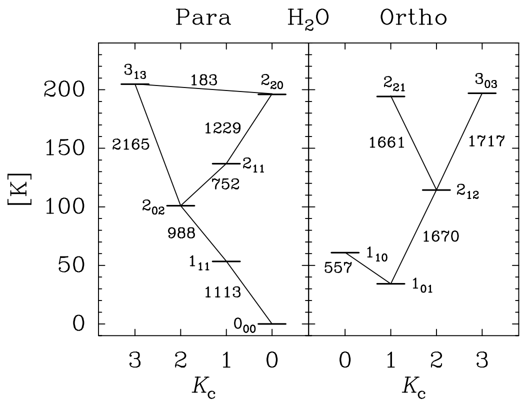

Fig. 2. Energy levels of the lowest rotational states of water with transitions labeled by the frequency in GHz. The lines at 557, 752, 988, 1113, and 1229 GHz delineate the principal submillimeter windows.

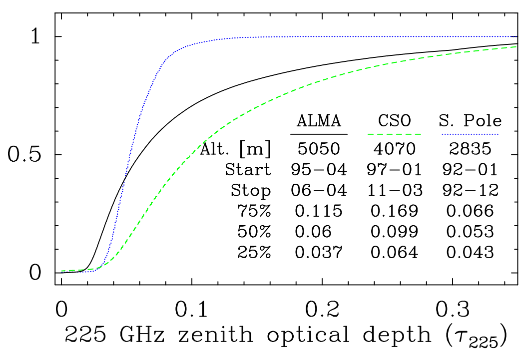

Fig. 3. Cumulative distributions of 225 GHz zenith optical depth measured with functionally identical narrow band heterodyne tipping radiometers on the Chajnantor plateau (ALMA), on the CSO on Mauna Kea, and at the South Pole (Chamberlin & Bally 1994; Radford & Chamberlin 2000). At the CSO, $\tau_{225} < 0.06$ is considered suitable for submillimeter observations.

sure the total atmospheric absoprtion, including all components, directly at a wavelength of astronomical interest.

5.1. *225 GHz measurements*

Functionally identical 225 GHz heterodyne radiometers, initially developed by NRAO for characterizing potential mmA sites, have been deployed to Mauna Kea, to the South Pole, and to the Chajnantor plateau (Figure 3). All three sites enjoy periods of excellent transparency suitable for submillimeter observations, $\tau_{225} < 0.06$. Mauna Kea, however, experiences these conditions about half as often as the other two sites. Poor conditions are very rare at the South Pole. During the best conditions, the 225 GHz transparency at the Chajnantor plateau is better than at the South Pole.

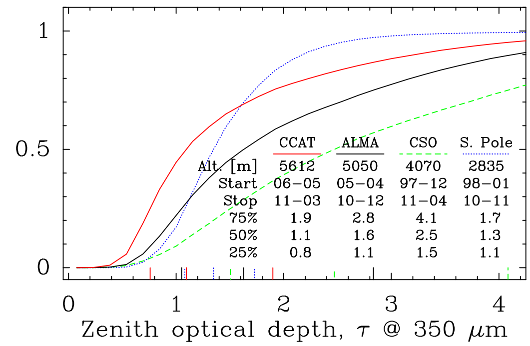

Fig. 4. Cumulative distributions of 350 μm zenith optical depth measured with functionally identical broad band tipping radiometers near the summit of Cerro Chajnantor (CCAT), on the Chajnantor plateau (ALMA), at the CSO on Mauna Kea, and at the South Pole. Measurements adjusted for radome transparency (Calisse 2004).

5.2. *350 μm measurements*

Because of the uncertainties inherent in extrapolating from 225 GHz measurements to higher frequencies, broadband tippers were deployed to directly measure the 350 μm atmospheric transparency. These instruments were developed jointly by NRAO and Carnegie Mellon University. The distributions of the 350 μm measurements (Figure 4) and the 225 GHz measurements (Figure 3) are quite similar. The first quartile 350 μm transparencies at the Chajnantor plateau and the South Pole are roughly equal and noticeably better than at Mauna Kea.

Seasonal variations are significant (Figure 5). At all three sites, the transparency is better during the winter than the summer. At the South Pole, conditions are remarkably consistent from year to year. The seasonal pattern for Mauna Kea, although evident, is overshadowed by year-to-year variations. In the Chajnantor region, conditions are consistently good from April through December but deterioriate during the summer months when a shift in atmospheric circulation patterns draws moist air over the Andes from the Amazon basin. There is considerable year-to-year variation in the severity of this summer season. Winter conditions in the Chjanantor region have less interannual variability than at Mauna Kea.

Both the Chajnantor region and Mauna Kea experience diurnal transparency variations, with better conditions at night. These diurnal transparency variations lag behind the solar cycle. The best conditions occur around sunrise. At Chajnantor, the diurnal variations are weaker during the winter than during the summer.

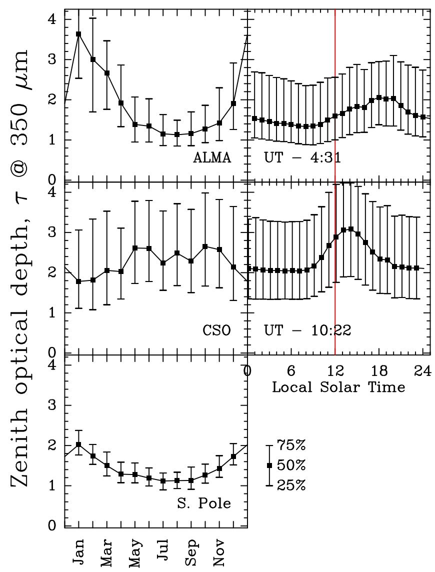

Fig. 5. Variations of the 350 μm zenith optical depth measured and on the Chajnantor plateau (ALMA), at the CSO on Mauna Kea, and at the South Pole. The error bars show the quartiles for each month or hour.

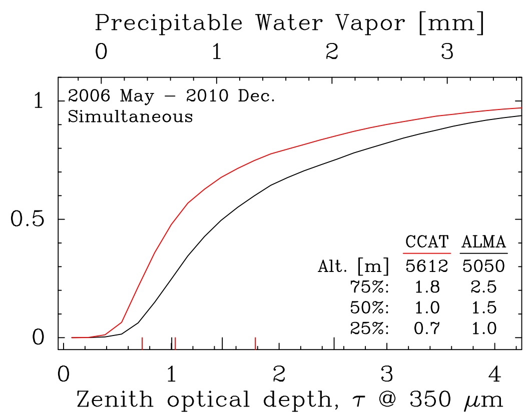

Fig. 6. Cumulative distributions of 350 μm zenith optical depth measured simultaneously near the summit of Cerro Chajantor (CCAT) and on the Chajnantor plateau (ALMA). This PVW scale is only appropriate for the Chajnantor region.

6. CERRO CHAJNANTOR

In the Chajnantor region, several peaks rise more than 500 m above the plateau. Radiosondes launched from the plateau measured the water vapor density profiles and have determined the typical scale height is about 1.1 km. The flights also revealed inversion layers frequently occur, especially at night, that trap moisture below the below the height of these peaks (Giovanelli et al. 2001). CCAT is a proposed 25 m diameter telescope for submillimeter astronomy (Radford et al. 2010). The candidate CCAT site is a level bench 5612 m high near the summit of Cerro Chajnantor accessed by a road constructed by the University of Tokyo. With two tipping radiometers, one at the summit and the other on the plateau, the 350 μm transparency was measured simultaneously. Prior to deployment to Cerro Chajnantor, the instruments were were operated side by side on the plateau where they reported identical results. Observing conditions for CCAT are significantly better than on the plateau (Figure 6), offering more opportunities for observations at short wavelengths. The 350 μm optical depth measurements on the Chajnantor plateau are well correlated with PWV measurements from a 183 GHz spectrometer on the APEX telescope. Linear regression then indicates PWV $= 0.935\ (\tau_{350} - 0.35)$. This relation is only appropriate in the environs of Chajnantor.

It is a pleasure to thank the many colleagues who have contributed to these measurements. Jeff Peterson initiated development of the 350 μm tippers. CCAT site evaluation is carried out in the Parque Astronómico Atacama in northern Chile under the auspices of the Programa de Astronomía, a program of the Comisión Nacional de Investigación Científica y Tecnológica de Chile (CONICYT). CCAT site evaluation received partial support from the National Science Foundation (AST-0431503). The NRAO is a facility of the NSF operated under a cooperative agreement by Associated Universities, Inc. The Caltech Submillimeter Observatory (CSO) is operated by the California Institute of Technology with funding from the NSF (AST-0838261).

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